Continuous heating of a giant X-ray flare on Algol

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Giant flares can release large amounts of energy within a few days[1−7]: X-ray emission alone can be up to ten percent of the star's bolometric luminosity. These flares exceed the luminosities of the largest solar flares by many orders of magnitude, which suggests that the underlying physical mechanisms supplying the energy are different from those on the Sun. Magnetic coupling between the components in a binary system or between a young star and an accretion disk has been proposed[3,7−9] as a prerequisite for giant flares. Here we report X-ray observations of a giant flare on Algol B, a giant star in an eclipsing binary system. We observed a total X-ray eclipse of the flare, which demonstrates that the plasma was confined to Algol B, and reached a maximum height of 0.6 stellar radii above its surface. The flare occurred around the south pole of Algol B, and energy must have been released continously throughout its life. We conclude that a specific extrastellar environment is not required for the presence of a flare, and that the processes at work are therefore similar to those on the Sun.

X-ray and radio observations have produced copious evidence for magnetic-field related activity on nearly all cool stars with outer surface convection zones[10,11]. Magnetic activity on other stars is usually interpreted by analogy with the Sun, viewing the observed stellar emissions as coming from scaled-up versions of directly observable solar features. The physical validity of this approach is debatable, particularly for the observed extremes of stellar activity, which exceed the corresponding solar emissions by at least five orders of magnitude.

Magnetic reconnection is important in the theory of solar flares[12], yet the application of the theory to solar observations produces ambiguous evidence for the occurrence of

reconnection[13,14]. Reconnection is a local phenomenon; the difficulty lies in explaining how energy can be released swiftly and coherently from rather small volumes. This becomes even more difficult when discussing the energetics of giant stellar flares. At peak, such flares can release up to a few percent of the quiescent bolometric luminosity, and their overall energy release equals the cumulative output of a few hours of quiescent luminosity; there must be, therefore, be an efficient way to first store, and then release, vast amounts of energy. Extreme levels of activity are observed in close binary systems and in very young stars, where the magnetic field topology is likely to differ from that of the Sun. In a close binary system, magnetic field lines may connect the two components, enabling plasma to be magnetically confined over a much larger interbinary volume; similarly, in a star surrounded by an accretion disk magnetic field lines originating in the photosphere may thread the disk and magnetic stresses may be built up by shearing motions. It has therefore been proposed that the specific environment of such systems is a prerequisite for the occurrence of giant flares[3,7−9].

In eclipsing binaries, size information can be obtained from light curves. The eclipsing binary Algol is among the nearest and X-ray brightest eclipsing systems; the relevant system parameters[15] are given in Table 1. Frequent X-ray flares have been reported on Algol[4,16,17] and the absence of an X-ray eclipse at optical secondary minimum has been interpreted as evidence for a corona with a scale height of more than a stellar radius[18]. A 2.9 day X-ray observation of Algol, covering the whole binary orbit, was carried out with the Italian BeppoSAX satellite[19]. Here we discuss only the medium energy concentrator spectrometer (MECS) light curve in the energy band between 1.6 - 10 keV. In Fig. 1 we show the phase folded BeppoSAX MECS light curve of Algol which is dominated by a huge flare lasting almost through the entire observation. The observed peak luminosity is 3×10^{32} erg/sec (at least 1.2 % of the late-type component's quiescent luminosity), and integration over all of the available BeppoSAX light curves yields a total observed X-ray energy release $E_{X-ray,tot} \approx 1.5 \times 10^{37}$ erg in the 0.1 - 10 keV band; thus the flare is at least as energetic as the largest flares observed on RS CVn systems, T Tauri and proto-stars[1−7].

At phase $\phi\ = 1.5$ a count rate minimum is observed (cf., Fig. 1). The only plausible interpretation of this light curve feature is an X-ray eclipse of the flaring plasma by the early-type primary. Residual X-ray flux persists at minimum, but a number of indications suggest that flux to come from Algol's quiescent (unocculted) corona and not from the flare: At $\phi\ = 1.5$ the light curve is straight while it decreases and increases before and after that phase; at minimum the observed count rate is close to the count rates before flare onset, and also the observed count rate at minimum is very similar to the mean ROSAT all-sky survey count rate. It is thus reasonable to assume that the eclipse of the X-ray flare is total. In order to validate this assumption, we attempted to determine the appropriate quiescent emission level at phase $\phi\ = 1.5$. All values between 0.4 and 1.5 cts/sec can be chosen and need to be compared to the observed minimum rate of 1.08 cts/sec (cf. Fig. 2, upper panel). We thus estimate that at least 90% of the flare emission was occulted; as a temperature increase was detected only when the count rate being above 1.1 cts/sec, we assume in the following that the eclipse of the flare was total.

Three important features of the BeppoSAX X-ray light curve are evident: (1) a total eclipse of the X-ray flare by the X-ray dark early-type primary; (2) a symmterical pattern of eclipse ingress and egress with a shallow light curve decrease of $\sim$ 20 % followed by a steep decrease of the remaining 80 % on ingress and vice reversed on egress; (3) no evidence for any occultation of the flare plasma by the late-type secondary (no rotational modulation; note that because of synchronous rotation two different stellar hemispheres are in view at $\phi \sim 1.5$ during minimum and at $\phi \sim 1.0$ when the flare erupts). The occurrence of an eclipse at $\phi\ = 1.5$ indicates that the flare is associated with the secondary; the absence of rotational modulation then implies that the flare plasma must be located near one of the poles. The eclipse totality restricts the maximal height above the surface to $d_{AB}\ sin(i) = R_*$, where d_{AB} is the distance between the binary components Algol A and Algol B, i is the angle between orbit plane normal and line of sight, and R_* is the radius is the star, considerably less than a stellar radius. A three-dimensional view of the admissible flare locations is displayed in Fig. 3. The flare undoubtedly occurred above the south pole of Algol B and not in the interbinary region.

For the maximally available volume in Fig. 3 we derive a value of $V_{max} = 1.5 \times 10^{33}$ cm^3. Clearly, the actual flare is likely to occupy only some fraction f_{max} of V_{max}. ¿From spectral analysis[20] the total emission measure at the flare peak, $EM = n^2V$ = 1.33 $\times 10^{55}$cm^{-3}, and the temperature T = 1 $\times 10^8$ K can be determined. Hence, the flare plasma density n = 9.4$\times 10^{10}/f_{max}^{1/2}$ cm^{-3}, and the thermal pressure is 2.6$\times 10^3/f_{max}^{1/2}$ dyn cm^{-2}. Given these values the radiative cooling time[17] τ_{rad} = $\frac{3kT}{nP(T)}$, where k is Boltzmann's constant, and the cooling function $P(T) = 10^{-24.73}T^{0.25}$) (in CGS units), becomes $\tau_{rad} = 23600 \times f_{max}^{1/2}$ sec. This is much smaller than the observed light curve decay time scale $\tau_{dec} \approx 60000$ sec regardless of f_{max}. It seems logical to conclude that continued heating through continued energy release must be present throughout the flare. Of course, the flare plasma may cool conductively. Determining the conductive cooling time scale[17], we find $\tau_{cond} = 2530 \times f_{max}^{-1/2}$ sec by setting the adopted length scale $L = V_{max}^{1/3}$. This value of τ_{cond} is smaller than τ_{rad} for large filling factors; however, τ_{cond} is sensitively dependent on L, and we are thus unable to prove that $\tau_{cond} < \tau_{rad}$ holds.

Small heights above the surface and continued heating are characteristic properties of "two-ribbon flares" on the Sun[21]. The energy for continued heating is derived from the reconnection of (non-potential) magnetic fields of opposing polarity. If all of the released energy $E_{released}$ is derived from the magnetic energy in the volume V_{max}, the minimally required magnetic field strength B_{min} can be computed by equating $\frac{B_{min}^2\ V_{max}}{8\ \pi} = \frac{E_{released}}{f_{X-ray}}$, where f_{X-ray} denotes the observed fraction of the released energy. We find $B = 500/\sqrt{f_{X-ray}}$ G to be the (non-potential) pre-reconnection magnetic field that needs to be annihilated to meet the energy requirements. If, in addition, the hot X-ray emitting plasma generated in the reconnection process must be magnetically confined, field strengths of at least B = 256$/f_{max}^{1/4}$ G after reconnection are required.

Our finding that the Algol flare occurred above the south pole of Algol B, fits well to the presence "polar spots" in many rapidly rotating active binary systems[22,23]. While no magnetic fields measurements nor Doppler images have been made of Algol B, it is reasonable to assume the presence of such polar spots on Algol B. Photospheric magnetic field strengths[24]

on late-type stars are typically in the range 1000 - 2000 G, and these values should also apply to Algol B. These values are clearly a strict upper limit to the coronal magnetic field strengths.

A solar-like reconnection scenario thus appears to be most natural to explain all the observations of the giant flare on Algol. For physical consistency, magnetic fields of 500 G - 1000 G, much larger than in the corona of the Sun[21], must be present in the corona of Algol B at heights of up to half a stellar radius, extending over a volume of $> 10^{33}$ cm^3 and reconnected in the course of the flare. The flaring plasma is associated only with the late-type star, and the binary nature of Algol is irrelevant, at least for this giant flare. The flare does, however, also display several features not observed in solar flares. Solar flares are never observed in polar regions; instead they are confined to the active region belt at lower heliographic latitudes. The thermal plasma in the giant flare on Algol is dominated by temperatures of 1×10^8 K; such temperatures are occasionally observed in solar flares[25,26] as "super hot plasmas", but they contain only small fractions of the overall emission measure. The derived minimal plasma density is similar to the plasma densities of many solar flares[27], which would require a volume close to V_{max} to satisfy the observed energy budget. Higher densities with correspondingly smaller volumes can, of course, not be excluded; however, much higher densities quickly lead to implausibly large thermal pressures. Thus, the real challenge to theory is the construction of physically consistent reconnection based flare models with the observed stellar parameters and clarify the role of giant flares for the mass and angular momentum loss of active stars.

Table 1: System Parameters for Algol ($= \beta Per$)

Parameter	Primary	Secondary	System
Mass (g)	$7.54\ 10^{33}$	$1.64\ 10^{33}$	
Radius (cm)	$2.15\ 10^{11}$	$2.29\ 10^{11}$	
Spectral type	B8V	K2III	
Luminosity (erg/sec)	$5.95\ 10^{35}$	$2.44\ 10^{34}$	
Rotation period (days)	2.8673	2.8673	
Orbital period (days)			2.8673
Distance (cm)			$1.02\ 10^{12}$

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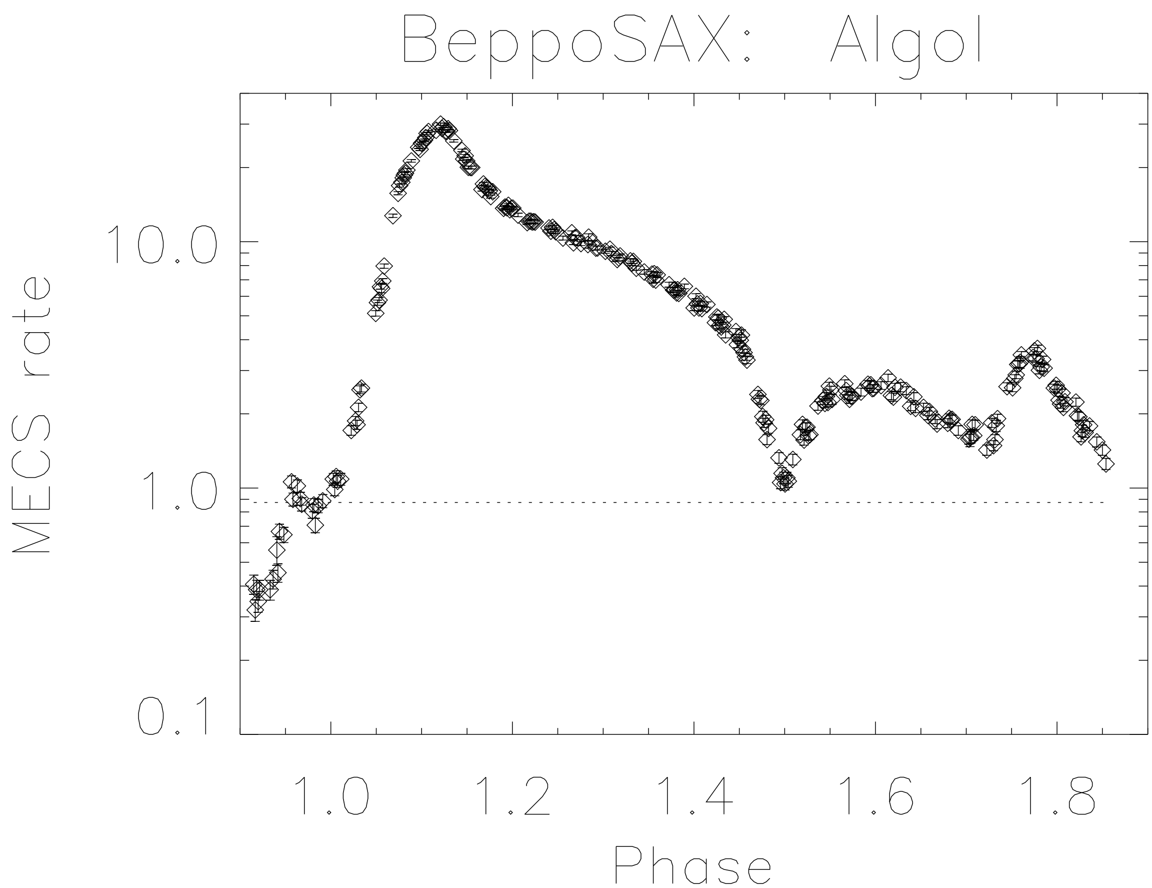

Fig. 1.— X-ray light curve of Algol measured with the SAX MECS2-MECS3 detectors in the 1.6 - 10 keV band between Aug 30, 1997 3:04 UT and Sep 1, 1997, 20:32 UT with phase ϕ calculated from the ephemeris JD = 2445739.003 + 2.8673285 $\times$ E (E integer) for the times of primary minimum[15]; a hundredth of a phase corresponds to 41.3 minutes. The phasing is such that for $\phi_E = E + 0.5$ the X-ray dark early type primary is in front of the X-ray emitting late type secondary. Note the huge flare starting at phase $\phi \sim 1.0$ with a rise time of about 8.3 hours and peaking at $\phi \sim 1.12$. A rapid initial decay until at $\phi \sim 1.25$ is followed by an exponential decay. A clear eclipse of the flaring plasma is seen at $\phi \sim 1.5$, when the early type primary is in front of the late-type secondary. The dotted line indicates an estimate of the quiescent out-of-flare rate, extrapolated from the observed ROSAT all-sky survey count rate.

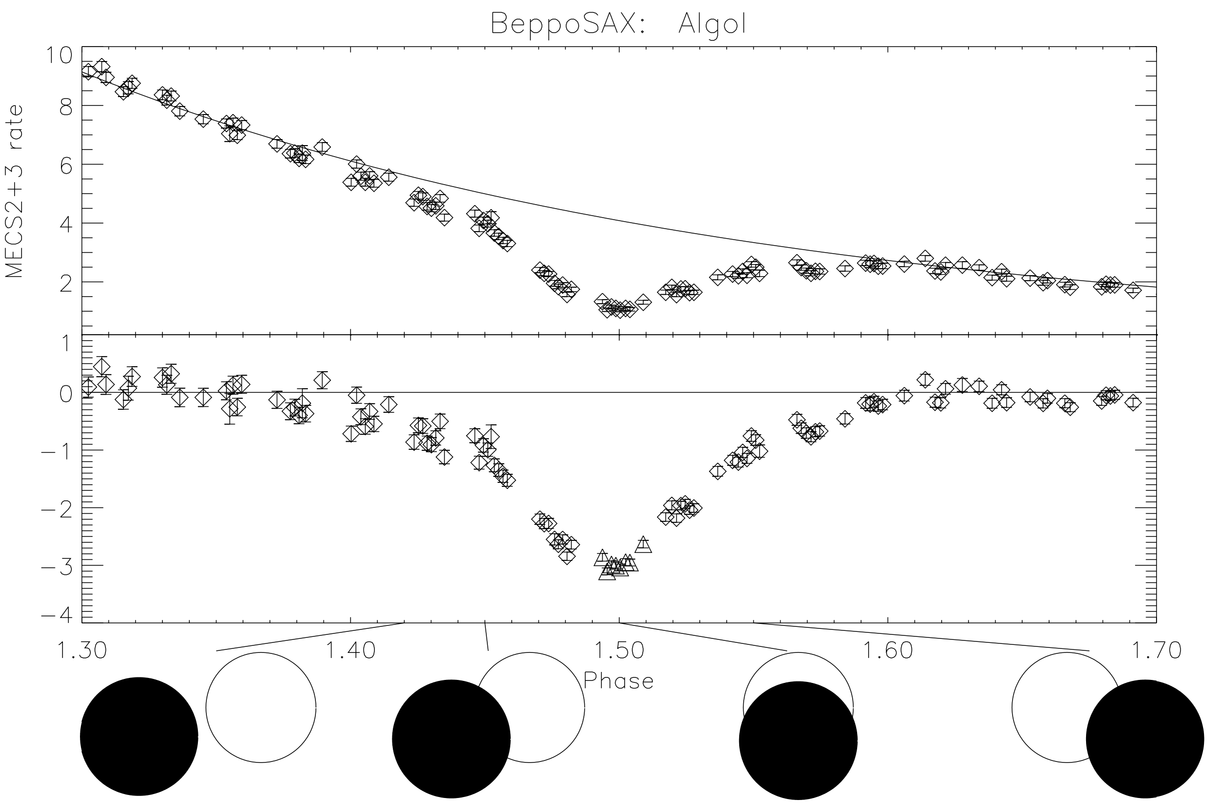

Fig. 2.— a) Upper panel: The MECS count rate vs. phase in the interval 1.3 - 1.7; the solid line represents an exponential fit to the pre- and post eclipse light curve. b) Lower panel: Count rate vs. phase in the interval 1.3 - 1.7 with exponential decay (shown in panel a) removed; the zero line is shown. The flare eclipse starts at $\phi \sim 1.39$ with a somewhat shallow decay, whence at $\phi \sim 1.451$ a sharp decay starts (first contact). Totality begins at $\phi \sim 1.488$ (second contact) and ends at $\phi \sim 1.505$ (third contact). The light curve increases quickly until $\phi \sim 1.545$ (fourth contact) and then more slowly until $\phi \sim 1.605$, when the flare eclipse is over. Below panel (b) the viewing geometry is shown at phases $\phi = 1.42$, 1.45, 1.50, and 155; the filled circle represents Algol A as it moves across Algol B.

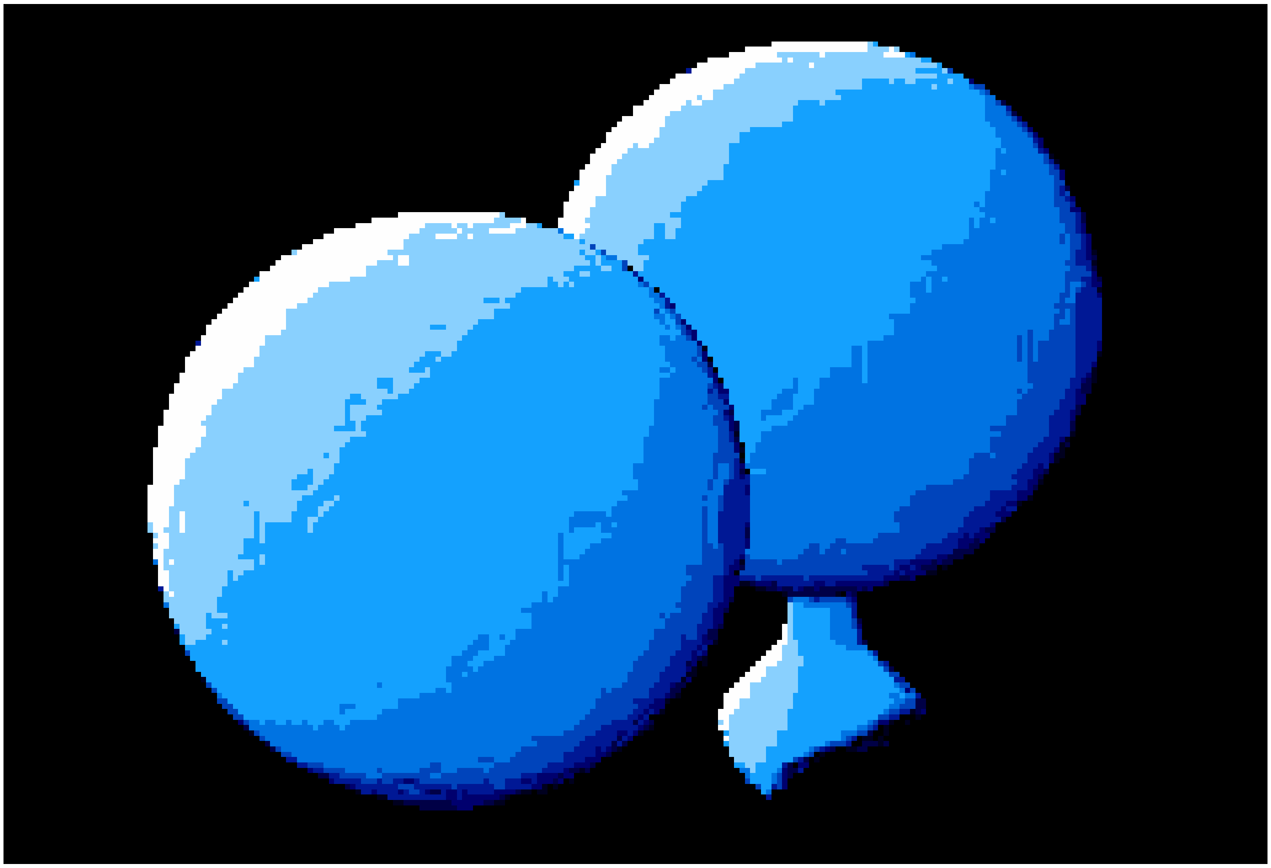

Fig. 3.— 3D-Visualisation of the Algol system including the maximum volume containing the flare. Shown are the two binary components Algol A (foreground) and Algol B (background) as seen from our line of sight at phase $\phi = 1.45$. The extension below the south pole of Algol B is the computed locus of all points satisfying the following requirements: (1) they must be totally eclipsed by Algol A between second and third contact; (2) they must be not eclipsed by Algol A and not occulted by Algol B itself before first and after fourth contact; (3) they must be visible between first and second but not between third and fourth contact or but not both; (4) assuming that the flaring plasma originates from the surface of Algol B, along any radial line of sight from the surface of the Algol B to the point under consideration there should be no more than twenty percent rotational modulation. These requirements define the hose-like structure above the south pole of of Algol B, within which the flare must have occurred. The flare is clearly associated with Algol B and did not occur in the interbinary region.